DISCUSSION ON

"GROUNDED-GRID AMPLIFIER VALVES FOR VERY SHORT WAVES"* AND "TRIODES FOR VERY SHORT WAVES—OSCILLATORS"†

BEFORE THE RADIO SECTION, 5TH MARCH, 1947

Mr. W. T. Gibson: The grounded-grid triode was a very great development in the early days of the war, at the time when it was necessary to extend the range of the 600-Mc/s radar, which the disc-seal tubes that have been described accomplished successfully.

The introduction of this novel type of receiving valve naturally brought in its train many manufacturing problems, and I think that the least of these problems was that associated with the copper-disc seal. Actually, it was really a continuation of the copper-disc Housekeeper seal, used 20 years before, in water-cooled valves for the filament leads.

One of the biggest troubles which we had was in securing an appropriate contact between the grid itself and the disc; this contact was made by 8 light springs of molybdenum. It was found very difficult to control the temper of these springs so that all eight made contact simultaneously; they might be too strong and deform the grid or, in some cases, the copper disc, or they would not make contact. A very careful inspection was necessary to ensure that all the springs made contact in every valve which was produced. Eventually, special methods of heat treatment of the molybdenum were worked out in order to control the springs.

Another point of interest in the manufacture of these valves was that the most essential feature was the low noise-level. As has been pointed out, the equivalent noise resistance was 350 ohms, and to keep this under control it had to be measured. This measurement was included as a part of the regular routine production testing, for which special equipment was included; at some times tests were made on the whole of the product, and at other times on only a proportion of the product.

Another interesting problem was that associated with the development of the CV88 from the CV16, the difference being that the CV88 had concentric cathode and heater lines, made of copper tube with an alloy wire sealed through it. The copper tube and the surrounding foot-tube, together with four supports for the electrodes, were all pressed in a single operation while the glass was hot.

I think that the paper does not bring out clearly the very vast amount of work done to extend the results which had been obtained at 600 Mc/s–3 000 Mc/s. A vast number of valves of different types were produced. One of the biggest problems encountered initially was that of connecting the grid to the disc. It was soon found that the springs used in the CV16 were totally inadequate when the frequency was raised, and it was necessary to connect the grid solidly to the disc. Various methods were worked out which culminated in the use of the copper grid, which was made by the electrolytic process referred to in the paper.

One of the biggest troubles which we had was that, as the work proceeded with the development of the valve for 3 000 Mc/s, the goal receded. At the beginning of the work a certain noise factor existed in the receivers due to the noise of the then-best crystals. As the valves were improved, so the crystals were improved, and the crystal always remained just a little better than the valve.

Another problem was the relative expansion of the cathode supports with respect to the glass envelope. The clearances which had to be used between grid and cathode were very small—measured in thousandths of an inch—and during the processing of the valve the cathode had to be heated to higher than normal temperatures. Very frequently the spacing disappeared altogether and a short-circuit occurred. Various means were therefore tried to avoid that, including such things as expansion joints in the copper tube forming the cathode line, which could be operated from outside the valve, so that during the exhaust, when the temperature was higher than normal, the cathode could be pulled away from the grid, and afterwards it could be adjusted to the optimum distance.

The final attempt to deal with the problem in this form was a type of valve due to Mr. Smyth, and commonly referred to as "the collar stud," because of its appearance; it is described briefly in the paper. There are one or two interesting features about it. The valve was made in two halves, each consisting of two discs of metal with a short length of glass tube, about 1 cm or rather less, joining them. At one end the disc carried a central spike which formed the anode, and the other disc carried the grid. In the other half, one disc again was associated with the grid, and the other one carried the cathode. The total length and the cathode-grid distance were so short that the relative expansion of the envelope and the cathode line was negligible. The grid was placed between the two grid discs which I have mentioned. These units were adjusted by jigs, so that the placing of the anode below the face of its associated grid disc was very accurately controlled, and similarly the level of the cathode was very accurately controlled below the level of the associated grid disc. When the grid itself was placed between the two members, it was accurately spaced as required.

These two grid discs were copper-plated on the outside, and were then ground and polished to a very fine finish, so that when the two halves were put together they actually made a joint sufficiently tight for the valve to be exhausted without any appreciable leakage of air. A ring of pure tin was placed round the outside of these two discs and melted during the exhaust of the valve and sealed up the gap between the two discs. The surfaces had to be sufficiently smooth to prevent any appreciable leakage occurring before the melting of the tin, and the spacing so small that the tin would not be sucked through into the evacuated space. A number of valves of that type were successfully made, and they operated for a long time, but the manufacturing problems were never fully overcome.

It is interesting to note that, from very extended life-tests which we have made, the average life of the amplifier valves described in the paper under working conditions appears to be greater than 5 000 h and, that the average life of the oscillator valves is greater than 3 500 h.

Dr. Emrys Williams: In Section 1.4 of the second paper the

* Paper by J. FOSTER (see 1946, 93, Part IIIA, p. 868).
† Paper by J. BELL, M. R. GAVIN, E. G. JAMES and G. W. WARREN (see 1946, 93, Part IIIA, p. 833).

authors say that there are "two and only two ways" of adjusting the circuits attached to a triode so that oscillation takes place. The authors are, of course, restricting their attention to circuits of the type shown in Fig. 6, to which nearly all oscillator circuits tend at the very-high frequencies in question. But it seems that (although they have derived a truly general equation for this oscillator circuit) they have been looking at one particular variation of the circuit, namely that in which the three impedances are designed to be as far as possible reactances, whose total reactance shall vanish at the frequency of oscillation. This is apparent from equation (2), i.e. $C_3/C_1 > 1/\mu$, which is true only for a reactance circuit of this kind. There are, of course, all sorts of other possibilities if one is prepared to admit impedances which are predominantly resistive. I imagine that the authors' reason for excluding such possibilities is not so much the difficulty of realizing predominantly resistive elements at these frequencies, but rather that such circuits would inherently be less efficient than reactance circuits.

It is perhaps worth pointing out that while there are only two possible circuits if μ is positive (as shown in Table 1) there are four further possibilities if μ is negative, enabling Table 1 to be extended as follows:

	B_1	B_2	B_3
Class III ..	C	L	L
Class IV ..	L	C	C
Class V ..	L	L	C
Class VI ..	C	C	L

Negative values of μ are attainable either with two cascaded triode-stages or with negative-transconductance pentodes, neither of which is probably a practical proposition at these high frequencies. But the use of the phase-reversing properties of $\frac{1}{2}\lambda$ lines might permit the exploitation of these four further possibilities.

Mr. C. W. Earp: In expressing appreciation of what the valve engineer has done in providing a simple but efficient amplifier which does not oscillate, and an oscillator which does, I think that a valuable new tool has been provided for a number of purposes.

I want to mention, in particular, those special cases where the input source for an amplifier requires either a damping resistance or a correct terminating-impedance. For example, supposing a receiving aerial, such as a fixed-tune loop, is over-selective so that variation of sensitivity is excessive over the working or tunable range of the receiver, then if selectivity is obliterated by connecting a damping resistance across the loop a serious loss of signal/noise ratio may result. Damping by a feedback impedance, however, results in no inherent loss of signal/noise ratio, and the grounded-grid amplifier often represents the most convenient way of providing such damping.

Another important case is the one in which it is desirable to terminate correctly the receiving end of a transmission line from an aerial. In such a case, correct matching to a matching network or load resistance fundamentally introduces a new source of noise, and the theoretical noise factor is doubled. Now, while agreeing that it is often unnecessary to match a receiver to the signal source, I would mention the special case of long transmission-lines from aerials used for radio direction-finding purposes. An unmatched line is likely to provide marked variations of amplitude and phase distortion with frequency, and accidental differences between two or more lines are likely to involve differences of performance resulting in direction-finding errors. However, connection of the lines to grounded-grid amplifiers provides a most convenient and "noiseless" matching arrangement which yields a definite improvement of signal/noise performance.

Another use which I have made of grounded-grid technique is in the provision of a modulator or switching circuit at the end of a transmission line associated with a v.h.f. automatic radio direction-finder. The grounded-grid valve, in which the grid is grounded so far as r.f. potentials are concerned, but into which the l.f. modulating or switching wave is introduced, has provided a very convenient solution. What could be simpler than a 3-terminal device, where two inputs may be connected, one to each of two terminals, the third terminal providing the required output? In this application the inherent feedback produces a marked improvement in gain stability, and this feature is of considerable value, in that relative gain of two complementary modulators influences the estimation of the radio bearing.

Mr. E. H. Ullrich: The work described by Mr. Foster started in the valve laboratories of Standard Telephones and Cables about April, 1941, at the urgent request of the Admiralty. The Battle of the Atlantic was critical, and a gain in signal/noise ratio of the order of 10 db was required on the 50-cm radar equipment in use on board ship. The development turned out to be one of those very happy ones that we often dream about but very rarely come across, because everything worked well from beginning to end.

It was suggested to us that we should use a velocity-modulated device, but we rejected that idea very quickly on the grounds that a velocity-modulated device is one in which there is exchange of power between an electron beam and the input circuit, and an electron beam of the kind that was in use at the time would introduce noise into the input circuit and degrade rather than improve the signal/noise ratio.

The first proposal to use a grounded-grid triode of the type shown in the paper came from Dr. S. G. Tomlin, while the dimensioning of the electrodes and the electrode clearances was due chiefly to Mr. Foster himself. The first samples turned out to be good—rather an exceptional circumstance in valve development. The first measurements in the laboratory gave a gain of 9 db in signal/noise ratio. Confirmatory tests on echoes followed and sets appeared at once. The work began in April, and by the end of the year tubes were going out at the rate of about 100 per month.

After that success, there was a request for an earthed-grid amplifier to improve the performance of 9·1-cm crystal receivers. At the end of about nine months we had produced a triode which at 9·1 cm gave a power gain of 6 db or more, the cathode being, perhaps, slightly overworked, and a signal/noise ratio improvement of 2 db over the crystal receiver which had been given to us by T.R.E. as our criterion. But from that time on we met check after check: when that amplifier was taken to T.R.E. for confirmation it was found that the crystal performance had improved slightly, so that instead of a gain we had a loss of 2 db.

Laboratory samples of a triode oscillator were made which covered a range of about 1½ cm between 10 and 12 cm, giving 15 mW output, but by tacit agreement with the General Electric Company, who were working on the same project, we continued with amplifiers and they turned their attention to oscillators. We spent the rest of the war trying to keep valve development up to that of the crystal.

The first sample just mentioned differed from the CV16 in several ways. The most important was the elimination of the contact springs. In the CV16 the grid-wire support made contact with the grid disc by means of springs. These had too much inductance and had to be eliminated. When, however, no further progress could be made, work was done on another type,

the essential differences being that it was much smaller, the glass was reduced to reduce input losses and the input coaxial line was taken in the form of copper tube through the glass, instead of as a wire, so that the input circuit would be more nearly a perfect coaxial line. The results, however, were again 2 db down on the crystal, as the crystal had been improved.

The rest of the effort was devoted to finding means of making grids of closer mesh and closer spacings which would not be destroyed by short-circuit during processing: and finally we did obtain a performance which was 1 db better than that of the average crystal.

We know now that the difficulty was the "total-emission damping," discovered by Mr. C. N. Smyth, and caused by the electrons which leave the cathode and do not pass the voltage minimum but return to the cathode, thereby damping the input circuit and introducing noise in it.

Mr. R. E. Burgess (*communicated*): In Fig. 2(*a*) and in the corresponding equation below it, C_{ag} refers to the anode-*cathode* capacitance which is small by virtue of the screening action of the grid. Since the grid-cathode and grid-anode capacitances are assumed to be combined into the input and output circuits respectively, it is not possible to make a direct comparison with the circuit of Fig. 2(*b*), where the effect of these capacitances is included explicitly. The input admittance for the circuit shown in Fig. 2(*b*) is given by

$$y_i = \frac{(1 + \mu + j\omega C_1 r_a)(1 + j\omega C_0 Z_L) + j\omega C_1 Z_L - \omega^2 LA}{(r_a + Z_L + j\omega C_0 r_a Z_L) - \omega^2 LB}$$

where $A = C_1 + C_0(1 + \mu + j\omega C_1 r_a)$, and
$B = (C_1 + C_0)(r_a + Z_L) + C_0 Z_L(\mu + j\omega C_1 r_a)$

When transit time is significant, the input admittance is given by

$$y_i = y_\alpha\left(1 - \frac{G}{\mu + 1}\right)$$

where G is the value of V/v when the applied e.m.f. is in series with the cathode. The *impedance* of a space-charge-limited diode with transit angle α is given by

$$\frac{1}{y_\alpha} = \frac{1}{g}\frac{12}{\alpha^4}[(2 - 2\cos\alpha - \alpha\sin\alpha) - j(\alpha + \alpha\cos\alpha - 2\sin\alpha)] + \frac{1}{j\omega C}$$

Eqn. (1) is not equivalent to this.

In the expression given for the output admittance, it appears that G is not the same quantity as the G used in y_i, but is the value of V/v when an e.m.f. is applied in series with the *anode* circuit.

Would the author indicate in a little more detail the derivation of his expression for the power gain at frequencies where the transit time becomes significant?

It is necessary to draw attention to three important points which must be observed in calculating the noise factor of multi-stage networks. These are:

(*a*) The value of gain of the first stage required for including the effect of the noise of the later stages in the *available power gain*, i.e. the ratio of the power available at the output terminals (with the load in position but with the following stages disconnected) to the power available from the source. Thus, if a source of e.m.f. e and an impedance $(R_0 + jX_0)$ is connected to the input of the first stage, whose output impedance with the load connected is $(R_1 + jX_1)$, and Ae is the output voltage, the available power gain is

$$M = \left(\frac{A^2 e^2/4R_1}{e^2/4R_0}\right) = \frac{A^2 R_0}{R_1}$$

It should be noted that neither the *actual* power input to the stage nor the *actual* power delivered to the load is involved. The ratio of the actual powers, which is the gain as calculated by the author, is best termed the "transmission gain." The reason why the available power is of importance in noise calculations is that it gives a convenient single term $e^2/4R$ which, when divided by $kT\Delta f$, is a measure of signal/noise ratio.

In the case of the grounded-grid stage, we have, when all the impedances are resistive,

$$A = \frac{(\mu + 1)Z_L}{(\mu + 1)Z_g + r_a + Z_L}$$

$$R_0 = Z_g$$

$$R_1 = \frac{Z_L Z_{out}}{Z_L + Z_{out}} = \frac{Z_L[r_L + (\mu + 1)Z_g]}{(\mu + 1)Z_g + r_a + Z_L}$$

whence $$M = \frac{(\mu + 1)^2 Z_L Z_g}{[(\mu + 1)Z_g + r_a + Z_L][(\mu + 1)Z_g + r_a]}$$

In the case of an infinite load impedance, which is relevant when Z_L is regarded as forming part of the following stage, the power gain is

$$M = \frac{(\mu + 1)^2 Z_g}{r_a + (\mu + 1)Z_g}$$

When the aerial impedance Z_a in parallel with Z_k forms the cathode-grid impedance Z_g, the overall noise factor is increased by the factor $1/\eta$, and is given by

$$\frac{1}{\eta}\left(1 + \frac{R_N}{Z_g} + \frac{N - 1}{M}\right)$$

(*b*) The second point is that the thermal noise of the load Z_L must be included if it is assumed to form part of the grounded-grid stage, and this results in an additional term $\frac{Z_{out}}{Z_{out} + Z_L} \times \frac{1}{M}$ in the noise factor. If, on the other hand, Z_L is assumed to form part of the next stage, the latter's noise factor will take the thermal noise into account; in this case, however, the power gain M_∞, appropriate to $Z_L = \infty$, must be used.

(*c*) The noise factor of the succeeding portion of the receiver is the value appropriate to a source impedance equal to the output impedance of the first stage. It should be remembered, however, that the available power gain of the first stage must be calculated for the case of the second stage *disconnected* from it.

Mr. E. M. Hickin (*communicated*): From the point of view of the engineer seeking valves for operation in peace-time developments, I feel that the usefulness of these very thorough reviews could be increased by the inclusion of some data on the life and stability of valves, as well as the performance data already given.

For many war-time applications, lives of 100 h were ample; but 2 000 h is probably the absolute minimum that can be considered useful for point-to-point radio links for example, and many times this life is desirable.

Many applications in the field of telecommunications must involve unattended operation, and it will be the ability of valves to meet this requirement which will decide their use.

Mr. M. G. Scroggie (*communicated*): May I point out an inconsistency in the title of Mr. Foster's paper? If it had been "Grounded-Grid Amplifier *Tubes* for Very Short Waves" it would have been foreign but at least consistent. Since "earth," and not "ground," is the accepted British term, I can see no ground for departure from it in the present case, unless perhaps it is a delicate way of acknowledging the Anglo-American origin of the work.

Mr. D. M. Tombs (*communicated*): My remarks refer to Sections 1.4, 1.5 and 1.6. The proof that only two classes of directly-coupled oscillator (the prototype Hartley and prototype Colpitts) can exist, may be shown in a way that relates them directly to the most elementary properties of valves and circuits.

Assuming that resistance may be neglected, let X_1, X_2 and X_3 be any three reactances (the signs and magnitudes of which are yet to be chosen) to replace $Y_1Y_2Y_3$ of Fig. 6, and let I be the current circulating round X_1, X_2 and X_3.

In order to find a condition of resonance,

$$X_1 + X_2 + X_3 = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(A)}$$

To satisfy this requirement the sign of one must be different from the remaining two. Under this restriction equation (A) determines the frequency.

Because, in the nature of a valve, an increase of grid-cathode voltage (in the positive direction) causes a decrease in anode-cathode voltage, the sign of the reactances must be chosen so that when I flows in them, this 180° phase relation is met. Only if X_1 and X_3 have the same sign can this be done, for then I entering X_1 at G (Fig. 6) makes it positive, while at the same time flowing out of X_3 at A makes A negative.

Hence X_1 and X_3 must have the same sign . . . . . (B)

The impedance of the anode load will be of the form L/CR, where $R \to 0$, because of the initial assumption of negligible resistance. In such a case where the anode load-impedance is very great, the anode fluctuation is μ times the grid fluctuation. Because of this property of the valve, the circuit elements through which I flows must be chosen in magnitude to satisfy this relation.

Thus $$\frac{X_1}{X_3} \geqslant \frac{1}{\mu} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(C)}$$

From the accompanying Table, where all the possible combinations of reactance are set out, it can be seen that the only possible oscillatory circuits are those satisfying both (A) and (B). These are shown to be the prototype Hartley and prototype Colpitts, the distinction being most readily remembered by the sign of the grid-anode (X_2) reactance. A capacitance there implies a Hartley circuit, and inductance a Colpitts. At very high frequencies it is not always obvious how a circuit oscillates, but the clue is usually given when the sign of the reactance of the grid-anode element can be determined.

Sign of			Satisfies condition (*a*)	Satisfies condition (*b*)	Satisfies both conditions (*a*) and (*b*)
X_1	X_2	X_3			
+	+	+	no	yes	no
−	−	−	no	yes	no
−	+	+	yes	no	no
−	−	+	yes	no	no
+	−	−	yes	no	no
+	+	−	yes	no	no
+	−	+	yes	yes	yes (Prototype Hartley)
−	+	−	yes	yes	yes (Prototype Colpitts)

Condition (A) determines the frequency, and (C) the amount of feedback for the inception of oscillations.